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EYE ACCOMMODATION TO HEAD-UP VIRTUAL IMAGES

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The head-up display (HUD) was developed to provide the pilot simultaneous viewing of flight information and the outside environment. The HUD optics were collimated so that the symbols appear at optical infinity as does the distant terrain. Operationally, about 30 percent of pilots experience an increased tendency toward spatial disorientation when using a HUD. Two experiments were conducted at NADC to determine whether HUD symbols do in fact cause the eyes to focus at optical infinity. And, if not, what is the direction and amount of refocusing necessary to see both distant targets and HUD symbols clearly? Results showed that use of the HUD releases accommodation to lapse inward toward the dark focus, or resting distance. When simultaneously using the HUD and viewing distant outside targets, only 3 of 10 subjects consistently focused at or beyond optical infinity; two of these had dark foci near infinity, and the third had a dark focus almost three diopters negative. Previous research indicates that when focus shifts occur, the apparent size and distance of objects also change. Spatial judgments critical to ground-referenced flight can be fatally erroneous. Because individual differences in focusing are large, redesigning HUDs to incorporate manual optical adjustment may be desirable to optimize focus demand for each pilot. Volitional accommodation training should also be investigated.

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INTRODUCTION

The intention of head-up display (HUD) designers is to provide a means whereby pilots can simultaneously focus on the real world and on displayed symbology. To make this possible, optically collimated virtual images are projected onto a combining glass mounted above the aircraft's instrument panel. The assumption has been that the eyes focus at optical infinity when viewing collimated images that appear to emanate from optical infinity. Not until the late 1970s was it found that collimated images do not necessarily cause the eyes to focus at optical infinity (Hull, Gill, and Roscoe, 1982; Randle, Roscoe, and Petitt, 1980). More recently Norman and Ehrlich (1986) have added supporting evidence.

Since HUDs have been used operationally in aircraft, several problems have surfaced. About 30 percent of pilots report that using a HUD tends to cause disorientation, especially when flying in and out of clouds (Barnette, 1976; Newman, 1980). Pilots have also reported a tendency to focus at the near distance of the HUD combining glass instead of on the outside real-world scene (Jarvi, 1981; Norton, 1981). The resulting HUD myopia appears to be a special case of the more general phenomenon known as instrument myopia (Hennessy, 1975). Whatever the cause, many pilots find it necessary to reaccommodate when shifting attention between HUD symbology and the outside world.

For example, F-14 pilots have said that air-to-air targets are difficult to see when they are inside, or within two degrees of, the HUD-displayed Sidewinder diamond. Conversely, some pilots flying low level have said that they did not see the large 'X' that appears on the HUD as a pull-up cue. Unaccountably, between 1980 and 1985, the US Air Force lost 73 HUD-equipped airplanes whose pilots became disoriented or misoriented and flew into the ground (McNaughton, 1985). The objective of the present research was to determine the nature and extent of biased focusing responses that can lead to spatial misjudgments (Roscoe, 1984, 1985).

BACKGROUND

The tendency of eye accommodation to remain at or return to its resting position is opposed by the acuity demand of a visual task (Simonelli, 1979). The degree of positive or negative accommodation in or out from an individual's neutral position is determined by the spatial frequencies that must be resolved to perform the task and by the extent, orientation, retinal locus, and spatial frequencies of visible textural gradients surrounding task-related objects. As either a foveal target or surrounding texture is obscured by reduced illumination, reduced contrast from haze or other atmospheric attenuation, severely reduced field of view, or optical defocusing, stimulus adequacy is degraded, and focus lapses toward neutrality (Benel, 1979).

INTERMEDIATE RESTING FOCUS

The notion that the resting focus of the eyes might not be at optical infinity was advanced explicitly by several investigators in the 1930s (for examples, see Cogan's 1937 review). During the 1940s and 50s even more experimenters reported resting or "dark focus" accommodation values at an "intermediate" distance, usually at about arm's length (see Simonelli's 1979 review). But it was not until the 1970s with the invention of infrared tracking optometers (Cornsweet and Crane, 1970), laser optometers (Hennessy and Leibowitz, 1970, 1972), and polarized vernier optometers (Simonelli, 1979, 1980) that the dark focus was systematically studied (for reviews see Benel, 1979; Owens, 1976; Roscoe, 1984, 1985; and Simonelli, 1979).

During the 1980s the intermediate distance "hypothesis," as it was cautiously referred to during the 70s by Herschel Leibowitz and his students at Pennsylvania State University, is gradually being recognized as a fact by the scientific community. Its involvements in the "anomalous" empty-field, night, and instrument myopias and in the curious Mandelbaum (1960) effect are now supported by a solid experimental base (Benel, 1979; Hennessy, 1975; Leibowitz and Owens, 1975, 1978; Owens, 1979). Its involvement in the many violations of the size-distance invariance hypothesis, including the "moon illusion" and the "projection" of afterimages, is less well understood and accepted, though repeatedly supported by experimental evidence (Roscoe, 1984, 1985).

ACCOMMODATION AND SPATIAL ORIENTATION

The discovery of a relationship between accommodation and apparent size runs directly counter to conventional belief. Other things being constant, the apparent size of an object is proportional to the distance to which the eyes are focused. The correlation between the apparent size of the moon, for example, and focal distance (not apparent distance) is virtually perfect, within the small errors of repeated measurement (Benel, 1979; Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1983; Simonelli and Roscoe, 1979). Also in contradiction to the size-distance invariance hypothesis: with no objective change in a visual scene, the larger an object appears with changes in focal distance, the *nearer* it seems to be (Roscoe, 1984).

So where a particular eye focuses, within its accommodative range, depends jointly on the acuity demand of the task and the locus and character of visible texture, mainly in the lower half of the visual field and within the spatial frequency range of 0.5 to 14 cycles per degree (Benel, 1979; Owens, 1979). And, where the eye focuses affects not only image clarity and visual acuity but also apparent size and distance and, as a direct consequence, the angular displacement from the line-of-sight of individual objects and surfaces such as an airport runway or a desert terrain. It is now evident that flying mishaps, such as landing short or long and controlled flight into the terrain, frequently are directly attributable to nonveridical spatial judgments associated with misaccommodation.

VIRTUAL IMAGING DISPLAYS

The problems just described have been exacerbated by the use of collimated virtual imaging displays in aircraft and flight simulators. For many pilots these displays prevent the eyes from focusing at the real or simulated distances of outside objects (Hull, Gill, and Roscoe, 1982; Norman and Ehrlich, 1986; Randle, Roscoe, and Petitt, 1980). Evidently collimation releases the eyes to lapse toward the dark focus, and the bold symbology of typical head-up displays does not require sharp focusing for legibility. Thus, collimation does not cause the eyes to focus at optical infinity as the advocates of head-up and helmet-mounted displays assert, and the consequences are the inability of most pilots to attend concurrently to the collimated symbology and distant objects without conscious focus shifting and associated losses in distant acuity and veridical spatial orientation.

OPTOMETRIC VARIABILITY

The problem is complicated by several factors, the most notable being the great variability in individual focusing responses particularly in terms of the far point and dark focus. Individuals with far points of 0.5 and −2.0 diopters, respectively, may have comparable near acuity and contrast sensitivity, but there will be a vast difference in their visual performances in reading highway signs, spotting ground targets from the air, picking up bogies, and other tasks for which a distant far point offers a big advantage. In contrast, for near work such as scope reading, an individual's performance will be maximized when the viewing distance equals his or her dark focus (Johnson, 1976), thereby not requiring accommodative effort either in or out to maintain image clarity.

EXPERIMENTAL APPROACH

In view of the growing concern over the problems pilots are experiencing with collimated displays and the evident implication of eye focusing difficulties, two experiments were designed to quantify the effects of viewing and responding to collimated HUD symbology on eye accommodation in natural and artificial visual settings. The experiments were designed to answer the following questions:

- How is eye focus affected when using a HUD?
- What is the extent of refocusing that must occur to respond properly to both the outside world and the display symbology?
- Is the effect different for individuals with different dark foci?

The experiments were conducted outdoors in daylight. Two rooftops at the Naval Air Development Center, separated by a distance of 182m, were used. On rooftop number one were the subject and experimenter, a HUD, its associated electronics, an optometer to measure accommodation distance, and a microprocessor to control timing and data collection. The microprocessor was linked to a parallel-to-serial encoder that transmitted equipment-control commands to the remote rooftop via electrical cable. On the remote rooftop was mounted what we refer to as the "scoreboard." The scoreboard was a pentagonal carousel, each face of which was capable of displaying digits of a different size. Descriptions of the experimental equipment follow.

EXPERIMENTAL EQUIPMENT

HEAD-UP DISPLAY

A HUD built by Marconi Avionics for the A-4M light attack aircraft was used. The HUD receives driving signals from a microprocessor and projects the computer-generated symbology into the subject's forward field of view superposed on the outside world. The symbol color is the green produced by a P-1 phosphor. The experimental targets are stroke-written seven-segment numerals subtending a ½-degree vertical visual angle. The ratio of the character width to height is 3:4, and the stroke width is ⅛ of character height. These dimensions were chosen to represent the typical size of alphanumerics on operationsl HUDs. The HUD's circular field of view subtends 20 degrees from the viewing eye position. This position is 50 cm from the forward setting of the combining glass. The HUD was carefully tested to ensure proper collimation of projected imagery.

SIMULATED CLOUD

The view from inside a cloud was simulated through the use of a sheet of linen cloth mounted on a Styrafoam frame for stability and placed in the immediate field of view of the HUD. The material was such that light could pass through but shapes could not. The cloud subtended a 60-degree field of view when positioned at a viewing distance of 1 m from the subject's eyes.

SCOREBOARD

Distant real-world targets were provided by the scoreboard. The scoreboard was a large pentagonal wooden box painted flat black and mounted as a carousel on a rooftop 182 m from the primary experimental station. On each of its five faces (not counting the top and bottom) could be displayed seven-segment numerals of a given size, one numeral at a time. The scoreboard box was rotated to allow presentation of numerals of the sizes called for in the various experimental conditions.

The segmented numerals were constructed from strips of green Plexiglass filter material independently transilluminated with incandescent bulbs. By remotely switching the various segments on and off, numerals from 0 to 9 could be formed by the computer. Viewed from a distance of 182 m, the resulting appearance of the numerals matched that of the stroke-written HUD symbols in color, shape, and stroke ratio. Luminance of the scoreboard numerals of each size was approximately 2000 fL. With sun shields mounted on the scoreboard to improve numeral visibility in full sunlight, the contrast between illuminated and unilluminated segments was marginally visible, thereby creating a high contrast-sensitivity demand calling for accurate accommodation.

The vertical visual angels subtended by the scoreboard numerals were 1/8, 1/12, 1/16, 1/20, and 1/24 of a degree. These angles are equivalent to Snellen-chart acuities of 20/30, 20/20, 20/15, 20/12, and 20/10. The corresponding heights of the scoreboard numerals were 39.2, 26.2, 19.6, 15.7, and 13.1 cm. With the stroke widths of the characters 1/8 their height to match the HUD, the visual angles subtended by the stroke widths of the numerals were approximately 1.0, 0.6, 0.5, 0.4, and 0.3 minutes of arc. All but the largest numeral size required resolution equal to or greater than the 20/20 line of a Snellen chart.

POLARIZED VERNIER OPTOMETER(PVO)

The PVO is a device for measuring visual accommodation, the distance to which the eye is focused (Simonelli, 1980). This is done in the following manner. The observer reports whether three optically projected vertical bar segments appear aligned as a continuous vertical bar or whether the central segment appears displaced to the left or right of the upper and lower segments. The bars will appear aligned only when their optical distance corresponds to the distance to which the eye is focused. This distance, sensed by an optical encoder in the PVO, is then translated by a simple formula into the focal distance of the eye. When the subject reports the bars are aligned, the experimenter has a measure of the momentary static focus of the eye.

The observer sees the PVO bars reflected from a small combining glass placed immediately in front of one eye. Thus the observer can also perform meaningful visual tasks while looking through the combining glass. When a shutter within the PVO is opened for a brief period, about ⅓ s, the observer sees the vertical bars superposed on the background scene. The presentation of the bars does not affect the accommodative state of the eye. The "vernier" alignment of the central bar segment relative to the upper and lower segments is easily discerned, and the observer indicates left, center, or right by pressing one of three correspondingly arranged pushbuttons.

In practice, to measure focal state while an observer is performing a visual task, the bar segments are presented several times intermittently over a period of about 20 s. After each presentation, the experimenter changes the position of the bars based on the observer's report of the state of their alignment. Initially each change brings the vernier target closer to the position corresponding to the focal distance of the eye. When the approximate position is found, a bracketing procedure is employed, moving back and forth through the momentary focal distance. The change of position on successive presentations is narrowed until the observer reports the bars to be aligned. Several determinations of the position of alignment are made to insure reliability of the measured focal distance.

METHOD

SUBJECTS

Ten subjects, selected randomly from the enlisted personnel subject pool at NADC, participated in both experiments. All subjects were confirmed by the flight surgeon to have at least 20/20 uncorrected binocular vision and to be free of abnormal phorias. These criteria were chosen because they represent the visual retention requirements for Naval aviators. In addition each subject's near point and far point (accommodative range) were measured.

DESIGN

Experiment I was a single-factor repeated-measures design. Head-up display background texture was the independent variable with HUD symbology appearing either against a simulated cloud background or against a distant terrain background. The presentation order of these two conditions was counterbalanced across subjects. Accommodation was the dependent variable. Control conditions included focus responses to each background while looking through the HUD but with no symbols displayed, focus response to the HUD symbols displayed in darkness, and dark focus or resting accommodation. Controls were measured both before and after an experimental series. The dark focus was also measured at midseries.

Experiment II was a repeated-measures design with two factors, location of targets (two levels) and target acuity demand (five levels). Targets were located either on the scoreboard only or on both the HUD and scoreboard simultaneously. The presentation order of conditions was counterbalanced across subjects. Control conditions included focus response to the terrain background while looking through the HUD with no targets visible, focus response to the terrain with a HUD digit visible, focus response to a HUD digit displayed in darkness, and the dark focus. Controls were measured before and after an experimental series. The dark focus measure was also repeated at midseries.

PROCEDURES

For conditions in which the HUD was used, but not the scoreboard, subjects performed two tasks, a digit-addition task and the optometer-response task. A series of three digits between 0 and 9 was randomly generated by the computer. These digits were sequentially presented in the center of the HUD. The stimulus duration of each digit was 800 ms, and the interstimulus interval was 300 ms. The task was to add the second and third digits and to press one of two right-hand response buttons denoting whether the sum was odd or even. The first digit provided a cue to the location in the HUD where the next two digits would appear. Subjects were not required to respond rapidly and were instructed that guessing was permitted.

Also, during the last 400 ms of the 800-ms duration of the third HUD digit, the optometer bars flashed. The subject was required to push one of three left-hand buttons to indicate whether the central bar segment was to the left or right or centered with respect to the upper and lower bar segments. A "did not see" button was also available because the optometer bar flash could easily be missed if the head were slightly out of position. In the condition in which the scoreboard and HUD digits were presented simultaneously, the task was to add the third digits in the two series and indicate whether the sum was odd or even.

Thus, in either case the subject made two responses for each presentation of digits, a right-hand response to the addition task and a left-hand response to the optometer. The odd/even responses served to ensure that the subjects were in fact reading the scoreboard and/or HUD digits, whether correctly or not. The optometer response was used by the experimenter to readjust the optometer to a new distance and bracket the point at which the subject would see the optometer bars aligned. Following each adjustment, the experimenter initiated the presentation of another set of three digits to obtain another accommodation response. This process continued until the refractive state of the subject's eye to the HUD targets was determined.

RESULTS

DARK FOCUS MEASURES

Table 1 presents the dark foci for each subject taken before, in the middle of, and after each experiment. Before considering the effects of the various experimental manipulations involving the HUD, we will examine the effects of the dark focus itself. The differences in measured dark foci between experiments I and II could easily have occurred by chance ($F(1,9) = 1.71$, $p = 0.22$). However, pre-, mid-, and posttest measures within experiments showed a trend toward a difference ($F(2,18) = 2.68$, $p = 0.09$). By midtest, the dark focus tended to drift outward. In Experiment I, the dark focus drifted from +0.82 D to +0.68 D. In Experiment II, the drift was from +0.67 D to +0.47 D.

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
						Pretest					
I	2.00	2.20	0.85	0.35	1.50	0.50	1.05	0.40	−2.25	1.60	0.82
II	1.15	2.70	1.00	0.55	1.35	0.90	0.65	0.30	−3.20	1.30	0.67
						Midtest					
I	1.60	2.65	0.90	0.00	1.45	0.95	0.50	−0.10	−2.95	1.80	0.68
II	0.75	2.10	0.60	0.30	1.25	1.15	0.40	0.30	−3.40	1.20	0.47
						Posttest					
I	1.40	2.45	0.90	0.50	0.95	1.00	0.75	−0.10	−2.55	1.60	0.69
II	1.30	2.55	0.90	0.20	1.30	0.95	1.30	0.05	−2.80	1.15	0.69
						Average					
I	1.67	2.43	0.88	0.28	1.30	0.82	0.77	0.07	−2.58	1.67	0.73
II	1.07	2.45	0.83	0.35	1.30	1.00	0.78	0.22	−3.13	1.22	0.61

TABLE 1. Dark Focus (DF) Measures Taken During Experiments I and II Showing a Trend of Outward Drift by Midtest and the Subsequent Drift Back Inward by Posttest in Experiment II

Eye accommodation is controlled by the sympathetic and parasympathetic branches of the autonomic nervous system (Benel, 1979; Cogan, 1937; Melton, Purnell, and Brecher, 1955; Olmsted, 1944). One possible explanation for the outward shift is a sympathetic adrenalin response associated with cerebral activity (Gawron, 1979). However, by posttest, the dark focus drifted back inward, particularly in Experiment II which lasted about 1½ hours for each subject, twice the length of Experiment I. Possibly fatigue toward the end of Experiment II, with an associated parasympathetic response, caused the dark focus to drift back toward its pretest value.

Scatterplots of the relationship between the dark foci of the individual subjects and all other measures are shown in Figures 1 and 2 for Experiments I and II, respectively. These scatterplots clearly indicate that: (1) An individual's dark focus is highly predictive of all other focus measures, regardless of the viewing conditions, and (2) Some people with normal visual acuity never actually focus at optical infinity (0 D). The average correlation between dark focus and all other focus measures was 0.95 for Experiment I and 0.93 for Experiment II. Thus, knowing each individual's dark focus can account for 88% of the variability observed in all the focus measures.

Fortunately, Subject 9, who had normal acuity despite an unusually distant dark focus of −2.86 D, was included in the sample. His data emphasize the point that focusing responses tend to remain within a relatively narrow range about the dark focus, wherever it may be. No matter how demanding the acuity task at optical infinity, his focus never came inside −1.75 D. Conversely, subjects with dark foci closer than about 3 m (⅓ D) never focused all the way outward to 0 D. Only two subjects (4 and 8) frequently focused at or slightly beyond optical infinity. Table 2 is a summary of the correlation coefficients between the subjects' average dark foci for the two experiments and their focusing responses in the various experimental conditions, with and without Subject 9's outlying responses included.

Condition	*Experiment*	*All Subjects*	*Subject 9 Excluded*
HUD in Dark	I	0.945	0.815
Cloud	I	0.946	0.819
HUD in Cloud	I	0.901	0.706
Terrain	I + II	0.967	0.872
Terrain + HUD	I + II	0.952	0.806
Scoreboard	II	0.918	0.719
Scoreboard + HUD	II	0.939	0.782
Average Correlation, $\bar{r}$		0.938	0.798
Variance Accounted for, $\bar{r}^2$		0.880	0.620
Multiple R		0.984	0.952
Multiple R^2		0.970	0.910

TABLE 2. Product Moment Correlation Coefficients between the Individual Subjects' Focusing Responses in the Various Experimental Conditions and Their Average Dark Foci for the Two Experiments, with and without the Outlying Responses of Subject 9

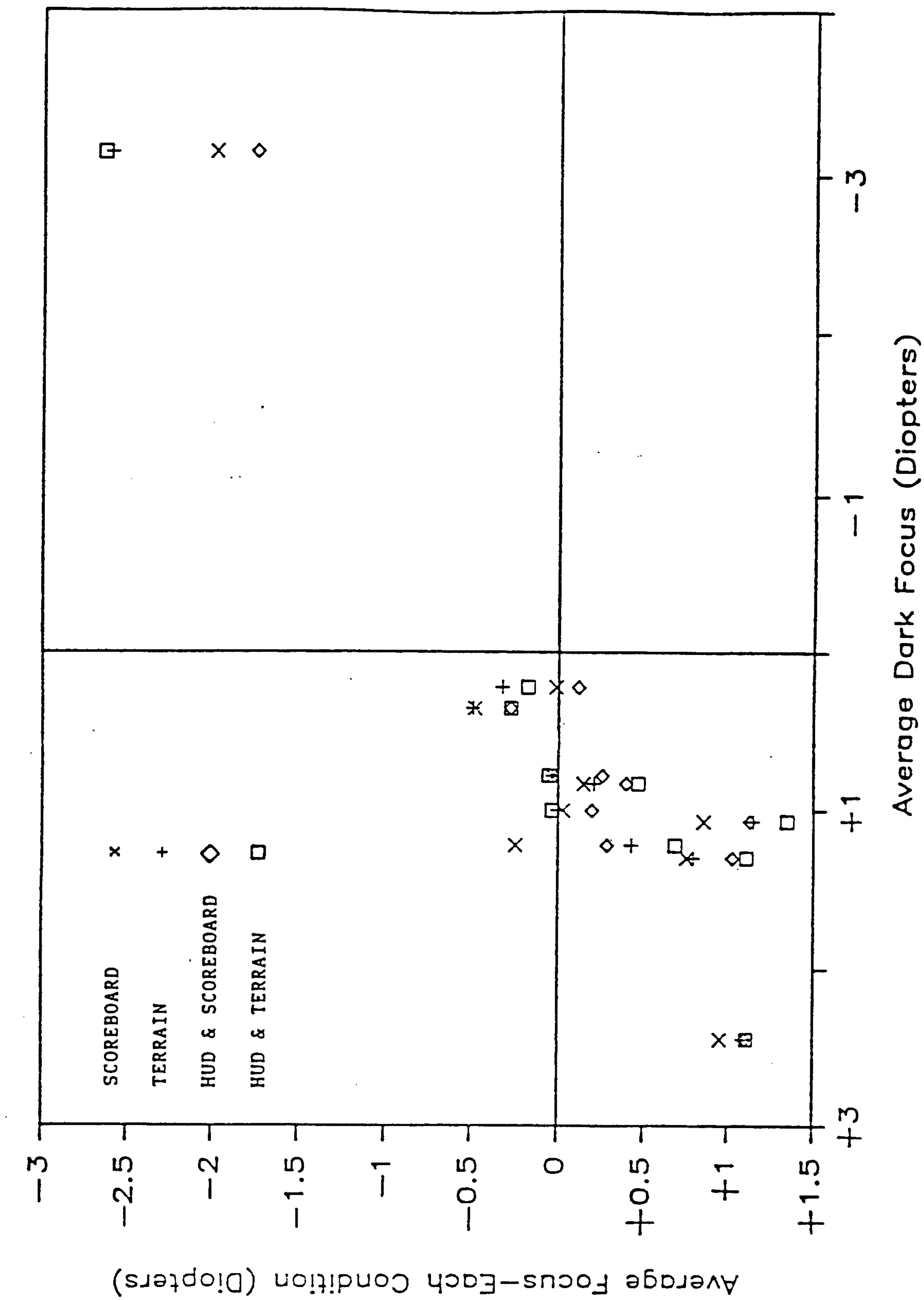

Figure 1. Correlation between average dark focus and all other focus measures taken in Experiment I.

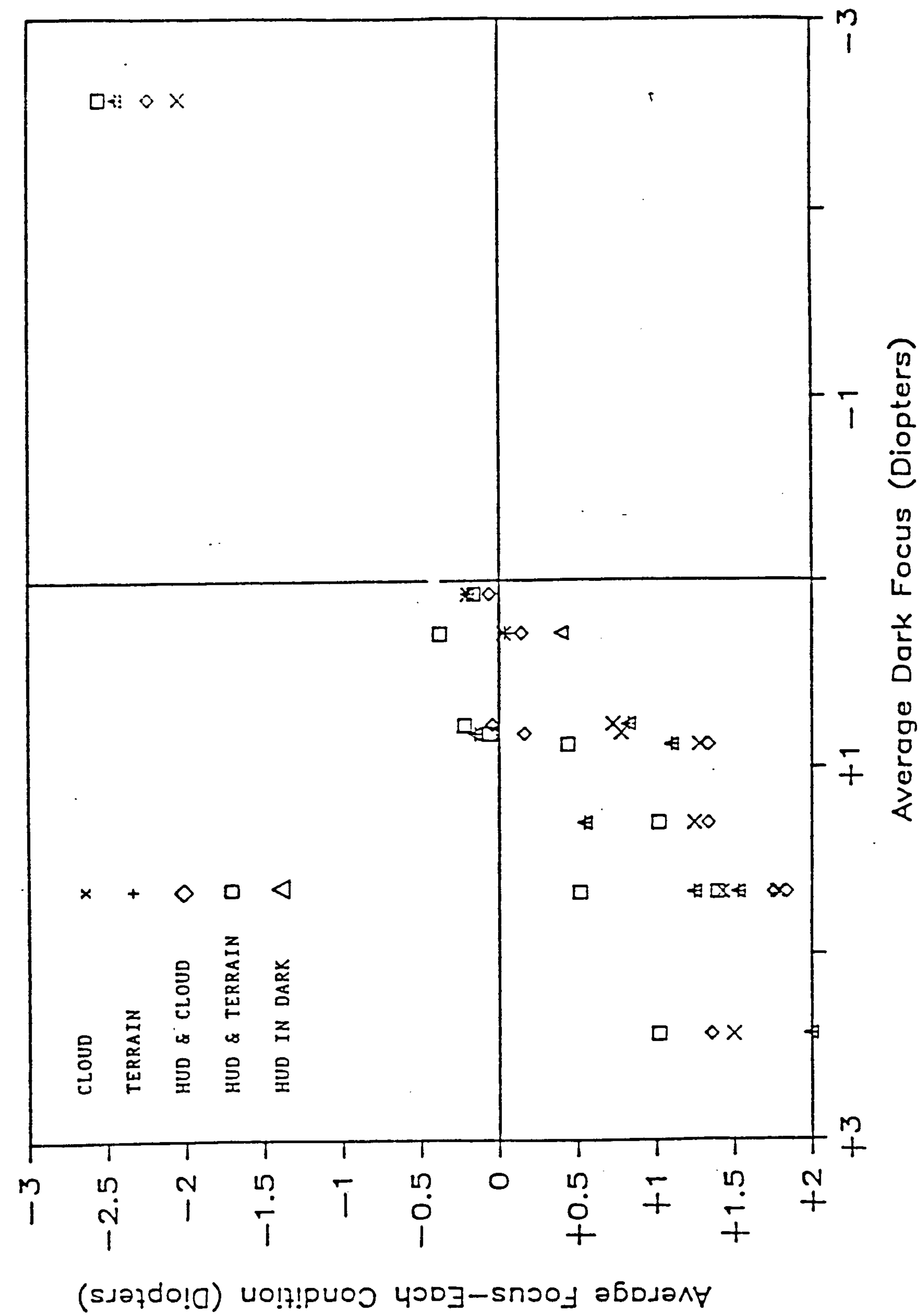

Figure 2. Correlation between average dark focus and all other focus measures taken in Experiment II.

OVERALL EXPERIMENTAL EFFECTS

The mean values of eye focus for the various experimental conditions in Experiments I and II are given in Table 3. It is evident that whether in the dark or in a cloud, the presence of the HUD symbology has little effect on focal responses. The small differences among the first four conditions in Table 3 could easily have occurred by chance. By itself a collimated virtual image does not draw accommodation to optical infinity. With the HUD symbology in use, focus shifted outward only 55 cm from the average dark focus of 149 cm (t = 1.25, p = 0.246) and only 27 cm from the average response of 152 cm to the cloud alone (t = 0.820, p = 0.434). Note that the average response to the cloud alone (the "light focus") was almost identical to the average dark focus.

Condition	*Experiment I* (D)	*Experiment II* (D)	*Composite* (D)	(1/D = Meters)
Dark Focus	0.73	0.61	0.67	1.49
HUD in Dark	0.49		0.49	2.04
Cloud	0.66		0.66	1.52
HUD in Cloud	0.56		0.56	1.79
Terrain	−0.01	0.06	0.03	33.33
Terrain + HUD	0.10	0.21	0.16	6.25
Scoreboard		0.00	0.00	inf.
Scoreboard + HUD		0.25	0.25	4.00

TABLE 3. Mean Values of Eye Focus in Diopters for the Various Conditions in Experiments I and II with Composite Values for Both Experiments Given in Diopters and in Meters

Conversely, when the HUD was turned on and used against an outside terrain background or a terrain plus scoreboard background, focal responses lapsed inward by large and statistically significant amounts. The lapse between the terrain only and the terrain plus HUD was from 33 m to 6 m (t = 3.07, p = 0.013), and the corresponding values for the terrain plus scoreboard conditions were optical infinity and 4 m (t = 6.98, p = 0.0001). Although there was wide variability among individual responses as a function of individual dark foci, the average response of the ten subjects to the scoreboard task with the HUD off was exactly at optical infinity (without Subject 9 it would have been 0.22 D).

INDIVIDUAL EFFECTS

The means of the focal responses of the individual subjects in each of the conditions in both experiments are given in Table 4. Because focus did not differ for the five digit sizes on the scoreboard, values for Conditions 6 and 7 are averages collapsed across digit sizes. One can think of any specific focal response as a compromise between the stimulus value, or pull, of the visible scene away from the dark focus and the pull of the dark focus to resist the active accommodation. For very close work, the shift is inward, or positive when expressed in diopters; for the outward responses induced in these experiments, negative shifts are obtained by subtracting the individual's dark focus value from the value for a given experimental condition, as shown in Table 5.

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
0. Average Dark Focus, Both Experiments	1.37	2.44	0.86	0.32	1.30	0.91	0.78	0.14	−2.86	1.44	0.67
1. HUD in Dark, Experiment I	1.25	2.00	1.10	0.40	0.55	−0.15	0.83	−0.20	−2.43	1.53	0.49
2. Cloud Only, Experiment I	1.78	1.50	1.28	0.03	1.25	0.78	0.73	−0.20	−2.03	1.43	0.66
3. HUD in Cloud, Experiment I	1.76	1.36	1.34	0.14	1.34	0.16	−0.04	−0.06	−2.22	1.84	0.56
4. Outside Terrain Only, Both Experiments	1.15	1.09	0.21	−0.49	0.80	0.00	−0.03	−0.32	−2.60	0.43	0.03
5. HUD plus Terrain Only, Both Experiments	1.35	1.11	0.47	−0.27	1.11	−0.03	−0.05	−0.17	−2.64	0.69	0.16
6. Terrain plus Scoreboard, Experiment II	0.86	0.96	0.15	−0.48	0.76	0.03	−0.03	−0.01	−1.99	−0.24	0.00
7. HUD plus Terrain and Scoreboard, Experiment II	1.13	1.10	0.40	−0.27	1.03	0.20	0.26	0.12	−1.75	0.29	0.25

TABLE 4. Individual Mean Dioptric Measures of Focusing Responses in the Various Experimental Conditions

	Subject										
	1	2	3	4	5	6	7	8	9	10	Mean
1. HUD in Dark, Experiment I	−0.12	−0.44	0.24	0.08	−0.75	−1.06	0.05	−0.34	0.43	0.09	−0.18
2. Cloud Only, Experiment I	0.41	−0.94	0.42	−0.29	−0.05	−0.13	−0.05	−0.34	0.83	−0.01	−0.01
3. HUD in Cloud, Experiment I	0.39	−1.08	0.48	−0.18	0.04	−0.75	−0.82	−0.20	0.64	0.40	−0.11
4. Outside Terrain Only, Both Experiments	−0.22	−1.35	−0.65	−0.81	−0.50	−0.91	−0.81	−0.46	0.26	−1.01	−0.64
5. HUD plus Terrain Only, Both Experiments	−0.02	−1.33	−0.39	−0.59	−0.19	−0.94	−0.83	−0.31	0.22	−0.75	−0.51
6. Terrain plus Scoreboard, Experiment II	−0.51	−1.48	−0.71	−0.80	−0.54	−0.88	−0.81	−0.15	0.87	−1.68	−0.67
7. HUD plus Terrain and Scoreboard, Experiment II	−0.24	−1.34	−0.46	−0.59	−0.27	−0.71	−0.52	−0.02	1.11	−1.15	−0.44

TABLE 5. Mean Dioptirc Shifts from Individual Dark Foci in the Various Experimental Conditions

In Figure 3 the averages of the responses to the terrain only and to the terrain plus scoreboard with the HUD On and Off are plotted relative to each subject's dark focus. These values were obtained by averaging the respective values from Table 5 for conditions 4 and 6 (HUD Off) and 5 and 7 (HUD ON) and subtracting the respective dark focus values. Figure 3 shows that, when the HUD is used, focus consistently shifts inward from optical infinity toward the dark foci of all nine subjects with positive resting values (but away from the extremely distant dark focus of Subject 9). The amount of the shift is a varying compromise between the pull of distant outside texture and the tendency of accommodation to lapse toward the dark focus when the HUD is used.

The consistency of the inward shifts from subject to subject shows that focus to the HUD plus real targets clearly is not the same as focus to the real targets alone. In fact, as shown in Tables 1 and 5, the HUD caused a larger lapse toward the dark focus when something on the terrain had to be seen and recognized as a target than when the terrain was not important. This comparison of focus to terrain targets alone with focus to HUD-plus-distant-targets is directly relevant to flying. Making veridical judgments of the distances and angular positions of surface objects is critical in ground-referenced operations such as landing, terrain following, and ground attack, and misaccommodation to the HUD is evidently implicated in the misjudgments that so often occur.

DISCUSSION

The two experiments reported herein demonstrate that where the eye focuses for *any* stimulus is greatly dependent on an individual's own dark focus. The eye tends to focus within a range around the dark focus distance, which appears to act as the starting point. Simply knowing an individual's dark focus accounted for 88% of the variability in focus over all the experimental conditions. How far the eye moves away from the dark focus is determined by the ambient conditions, the acuity demands of the visual task, and the existence and nature of a textural gradient extending either toward or beyond an object to be resolved. Nevertheless, we go through life not noticing that most of what we see is badly out of focus.

In fact, some people never actually focus at optical infinity, no matter how demanding the acuity task or how distant the texture gradient. This is particularly true for people whose dark focus is relatively close (like subjects 1, 2, and 10) or very far (like subject 9). Only people with a dark focus close to optical infinity tend to focus distant objects clearly. Thus, because most people have a dark focus that is closer than optical infinity, looking at and trying to resolve collimated targets will not result in infinity focus for many people with normal visual acuity.

In every condition the measured focus responses seemed to be a compromise between the pull of the dark focus and the pull of the visual task at hand. When the terrain contained a demanding acuity task, namely the scoreboard, the pull was greatest away from the dark focus. When the terrain contained no task, the pull from the dark focus was also large, although a little less distant than when acuity demand was present. However, whenever the HUD was used, whether alone or simultaneously with terrain targets, the eyes lapsed significantly toward their dark foci.

These lapses toward the individual's dark focus caused by the HUD can produce dangerous misperceptions by a pilot of his position in space. The relationship between accommodation shifts and changes in apparent size and distance of objects is now well established (Hull, Gill, and Roscoe, 1982; Iavecchia, Iavecchia, and Roscoe, 1983; Randle, Roscoe, and Petitt, 1980; Roscoe, 1984, 1985). When focus shifts inward, the apparent visual angle subtended by distant surface objects, such as an airport runway or a military target, shrinks, thereby causing the object to appear smaller and farther away than it actually is.

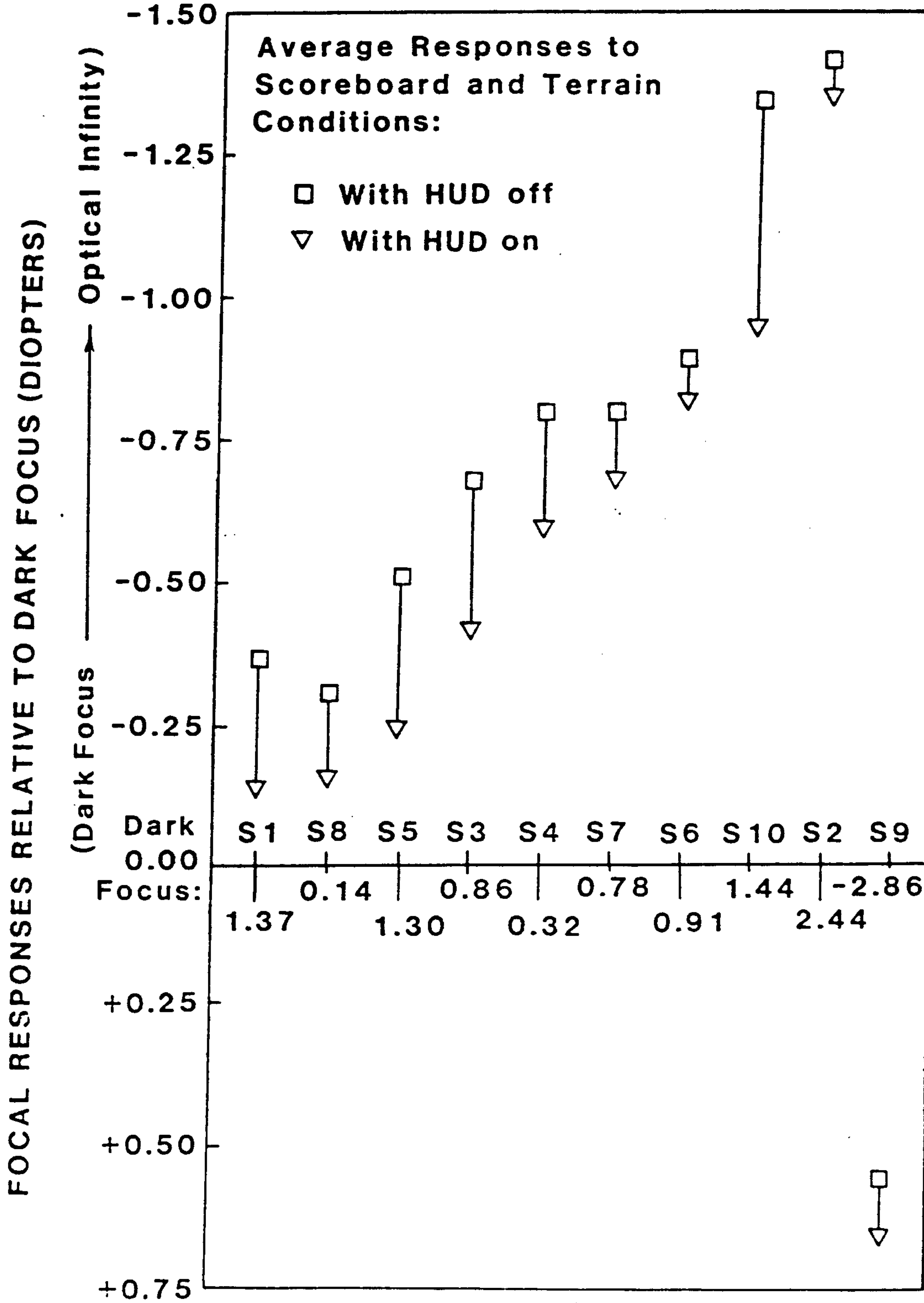

Figure 3. Average focal responses to the scoreboard and the terrain conditions with HUD On and Off, plotted relative to each individual's dark focus.

Surface objects not only appear smaller and farther away, causing pilots to overshoot on landing approaches, but the surface itself appears higher in the visual field, causing pilots to round out high and land hard. This effect has been demonstrated in flight simulators with visual systems (Palmer and Cronn, 1973; Randle, Roscoe, and Petitt, 1980) and in airplanes with flight periscopes (Campbell, McEachern, and Marg, 1955; Roscoe, 1950, 1984, 1985; Roscoe, Hasler, and Dougherty, 1966), both of which cause most pilots' eyes to focus too near, as does the HUD. Eventually the pilot will realize that he is overshooting, but by the time the misjudgment suddenly becomes apparent, the combined response capabilities of the pilot and the airplane may be too slow to avert the mishap.

Erroneous judgments of the aircraft's position in space relative to the terrain or objects in it can be expected, and these misjudgments can have disastrous effects, especially in low-level attacks. Of the 73 HUD-equipped USAF aircraft lost between 1980 and 1985, 54 involved controlled flight into the terrain. The remaining 19 were attributable to spatial disorientation, as opposed to misorientation. The average cost of the airplanes was $6,726,020, for a total cost of $491,000,000, plus the lives of the pilots and weapon system operators (McNaughton, 1985). Thus, a better understanding of the cause of the HUD-induced myopia is needed.

Because of the huge individual differences in dark foci and focal responses to stimuli, any particular correction in the HUD optics would not be appropriate for everyone, nor would any single value be optimum for flying at high altitude or in empty-field visibility conditions and also at low levels as in terrain following or ground attack. However, Owens and Leibowitz (1976) have shown that an optical correction equal to half the difference between a person's dark focus and optical infinity is best for night driving. In further support of this observation, Norman and Ehrlich (1986) recently found that a group of Israeli pilots, on average, focused near optical infinity only when a focus demand of −0.5 D was applied.

In view of the serious operational concerns about pilot disorientation and misorientation since virtual imaging displays have come into wide use, some corrective action is needed. To minimize the misjudgment problems associated with virtual imaging displays and to improve their safety and operational effectiveness, the least that will be required appears to be adjustable optical refraction, just as people who wear glasses require different amounts of correction. If a manual adjustment for differences among pilots' eyes is provided, inserting further minor corrections for specific task conditions would also be possible.

Until HUDs are manufactured with redesigned optics, training in volitional focus control for pilots flying HUD-equipped aircraft is a possible aid. A focus biofeedback conditioning technique developed by Randle (1970) has been used to induce partial remissions of behavioral myopia in teenagers (Randle, 1986). Even more recently, Roscoe and Couchman (1987) have shown that volitional focus control can be taught using a polarized vernier optometer and an extremely simple binocular focus stimulator. A limitation of volitional focus control is that it may fail in stressful situations, and it will not take away the fact that the HUD creates a constant tendency toward misaccommodation.

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